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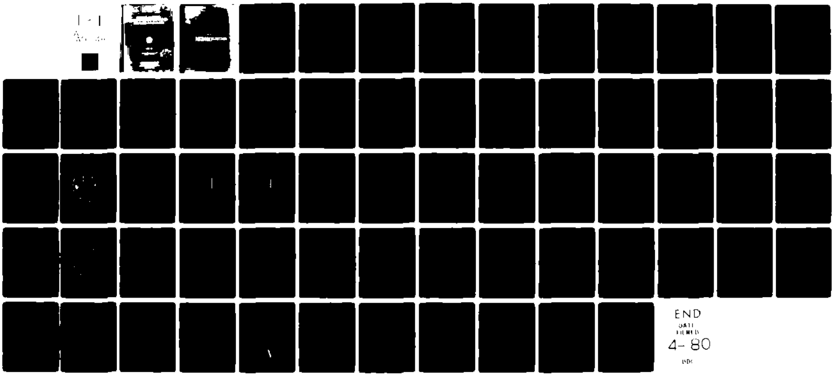

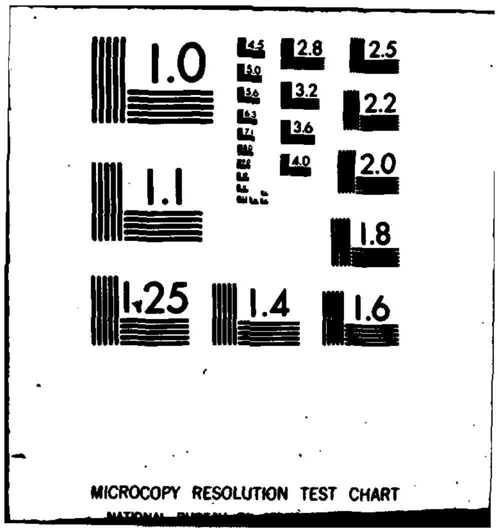
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Wake Vortex Avoidance System

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16. Abstract

A Wake Vortex Avoidance System (WVAS) may provide increased airport capacity by allowing for reduced aircraft separation standards on final approach under certain meteorological conditions. Three sets of reduced separation standards have been hypothesized in order to describe the operational characteristics of potential WVAS systems. Analyses develop several operational schemes which allow aircraft to transition to reduced separation standards when under WVAS coverage, while maintaining larger terminal area standards prior to intercepting that coverage. Specific applications of these schemes to Atlanta Hartsfield and Chicago O'Hare International Airports are also described. Other analyses investigate procedures for and dynamics of transitioning between different sets of separation standards. Capacity benefits corresponding to the utilization of the different sets of separation standards, under various operational procedures, are estimated for Chicago and Atlanta.

17. Key Words

Wake Vortex, Longitudinal Spacing, Airport Capacity, Transition, Vortex System Coverage, Missed Approach

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CONCLUSIONS AND RECOMMENDATIONS

Certain conclusions can be drawn from the analysis concerning the coverage requirements and relative capacity benefits of the three operational procedures investigated: accordion effect, vertical merging, and horizontal merging. The effects of different amounts of warning time before a required change in separation standards, with regard to probabilities of missed approaches and disruption of orderly traffic flow, have also been studied.

The use of the accordion effect to reduce spacings requires WVAS coverage up to the outer marker, about 5 miles from the runway threshold. This procedure achieves significant but partial potential capacity benefits. The vertical and horizontal merging schemes enable full capacity benefits to be attained from reduced separation standards where the minimum separation standard is as low as 2.0 nmi. These merging procedures require vortex system coverage of about 12 miles for a single runway, and approximately 17 to 20 miles of coverage for parallel runway configurations with independent arrivals on both runways.

A change in the required separation standards from smaller to larger standards requires a procedure which will avoid violation of the larger standards. This procedure consists of selecting particular aircraft to execute go-arounds, while using speed control to open or close the remaining gaps for aircraft on the localizer. The number of go-arounds and the required extension of the localizer intercept point (used to absorb traffic that have not yet intercepted the localizer) are dependent upon the amount of advance warning time given by the system before the new standards must be enforced. A warning time of 2.5 minutes results in a high probability of one or two missed approaches and a large extension of the downwind area. As the warning time is increased to about 8 minutes, the probability of missed approaches nears zero, but the large extension of the downwind area remains. A warning time of about 20 minutes allows stable transition between different standards, with no extension of the downwind area.

Comparing the hypothesized WVAS standards having 2.0 nmi minimum separation to today's IFR standards, the accordion effect can give approximately 28% increase in arrivals-only capacity (using the aircraft mixes observed today at Atlanta and Chicago). The use of either merging procedure yields an additional 16% increase in arrivals-only capacity.

The specific design of a future Wake Vortex Avoidance System should utilize the results of this study in incorporating the following parameters in its design tradeoff: (a) the type of standards involved, (b) the specific spacing reduction schemes, (c) vortex system coverage, (d) the availability of transition airspace, (e) the amount of warning time before a required change in standards, (f) the number of missed approaches considered acceptable, and (g) the associated capacity benefits.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Concluded)

1. INTRODUCTION

1.1 Background and Scope

Current air traffic control (ATC) procedures require increased longitudinal separation (4 to 6 nmi. as opposed to the minimum separation of 3 nmi.) on final approach between some aircraft pairs to protect the trail aircraft against a hazardous encounter with a vortex generated by the lead aircraft. These vortices do not always pose a threat to the trail aircraft at reduced separations due to the vortex transport and decay charcteristics. Significant increases in capacity (and hence, reductions in delay) can be achieved by reducing longitudinal separation standards under those conditions when vortices are not a hazard (Reference 1). Under today's ATC rules, the addition of more wide body aircraft will add to the existing delay problems at major airports. In an attempt to reduce this trend, the FAA established a wake vortex Engineering and Development (E&D) program whose goals include developing systems capable of detecting and predicting vortex behavior. The ground-based Wake Vortex Avoidance System (WVAS) concept is one result of this program.

This paper documents work done for the FAA's Office of Systems Engineering Management (OSEM) in developing operational procedures whereby reduced separations can be attained on final approach under WVAS coverage while maintaining larger terminal area standards prior to intercepting that coverage. The operational feasibility of these procedures is assessed, and procedures for and dynamics of transitioning to and from the reduced spacing standards are investigated. Finally, the capacity benefits associated with the utilization of these reduced spacing standards are estimated. Wake vortex alleviation systems provide an airborne alternative to the vortex problem and NASA has been conducting the research in this area. Any operational feasibility analysis of vortex alleviation systems is beyond the scope of this paper.

Previous papers (References 2 and 3) have developed a set of estimated separation standards and other parameters for use in studies relating to the assessment of future performance of elements of the FAA Engineering and Development program. These papers were used as guidance in determining the input values to the capacity model for comparison of the different vortex system configurations. No attempt was made in this study to provide an impact analysis of the vortex systems as they relate to productivity, efficiency, aircraft noise, or cost/benefit considerations.

Other papers (References 4, 5 and 6) have considered some effects of vortex systems operations at two airports, Atlanta International Airport and Chicago O'Hare International Airport. This analysis expands from the study performed in Reference 6 to determine the procedural feasibility of using Wake Vortex Avoidance Systems for both of the airports mentioned. Current operations at Atlanta and O'Hare Airports form the baseline of this analysis. The characterization of current operations was obtained primarily from References 4 through 7.

1.2 Methodology

The analysis presented in this paper is conceptually divided into five steps:

1. Definition of operational reduced separation standards.

2. Description of schemes for achieving reduced separation standards.

3. Enumeration of design parameters on which to base the selection of a specific scheme.

4. Characterization of flight operations at Atlanta and O'Hare Airports.

5. Application of schemes to Atlanta and O'Hare Airports along with considerations for transitioning from one set of standards to another.

The first three steps are discussed in Chapter 3, and the last two steps in Chapters 4 and 5 for Atlanta and O'Hare respectively.

2. WAKE VORTEX AVOIDANCE SYSTEM

A Wake Vortex Avoidance System (WVAS) is being developed to provide increased airport capacity by permitting reduced aircraft separation standards under certain meteorological conditions. Two levels of WVAS systems are envisioned. The first level, called the Vortex Advisory System (VAS), consists of a system of wind sensors located near the approach end of each runway. These sensors transmit data to a central processing computer for assessment of wind conditions which would lead to nonhazardous vortex conditions. A display will be provided to controllers indicating the presence or absence of vortices in the approach corridor. These indications are referred to as red or green light conditions respectively. Reference 8 contains a more detailed description of the Vortex Advisory System.

The second level of the Wake Vortex Avoidance System is to be an advanced system utilizing vortex sensors and a complex predictive algorithm to both measure and predict vortex movement and decay. The WVAS may allow closer spacing between aircraft under certain meteorological conditions compared to that which would be possible under the less sophisticated VAS. Whereas a modified version of VAS has been installed at O'Hare for testing purposes, WVAS is still in the conceptual stage.

3. *SPACING REDUCTIONS UNDER WVAS OPERATIONS*

3.1 Problem Statement

The problem addressed in this analysis is divided into two major parts. The first is to define operational schemes which will allow aircraft to transition to reduced separation standards under vortex system coverage* while also maintaining terminal area standards prior to intercepting that coverage. The second part is to investigate procedures for and dynamics of transitioning to and from reduced separation standards for two specific airports, Altanta and Chicago O'Hare.

The separation standards which are considered are diagrammed in Figure 3-1. These sets of standards were taken from Reference 2. The standards are presented in the form of matrices depicting the various pairings for the 3 aircraft types: small (S), large (L), and heavy (H). The small/large/heavy aircraft designation is as follows:

small - 12,500 pounds or less maximum gross takeoff weight (GTOW).

large - between 12,500 pounds and 300,000 pounds maximum GTOW.

heavy - 300,000 pounds or more maximum GTOW.

The separation matrix, which is used to label and define the various standards, shows for each aircraft type pairing, the minimum allowable separations at closest point of approach. The average spacing under actual operations for a particular aircraft pair will always be greater than that shown in the separation matrix, since a buffer must be added to account for delivery error.

3.2 Assumptions

There are four major assumptions made for this analysis. First, only IFR flight conditions are considered, since minimum separation standards are not defined for VFR. Second, the minimum system coverage is out to the outer marker. Vortex

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*The term "coverage" is used here to imply *an area of safe reduction* in separations as compared to today's standards. The "coverage" may be provided through sensors, wind measurements, better path following capability or acceptable hazard definitions.

Terminal Area (NMI)

LEAD \ TRAIL	S	L	H
S	3	3	3
L	3	3	3
H	5	5	4

Arrival/Arrival (NMI)

SET 1 (Today's)

LEAD \ TRAIL	S	L	H
S	3	3	3
L	4*	3	3
H	6*	5	4

*At Threshold

SET 2 (VAS)

LEAD \ TRAIL	S	L	H
S	3	3	3
L	3	3	3
H	4	3	3

SET 3 (WVAS 2.5 NMI Min.)

LEAD \ TRAIL	S	L	H
S	2.5	2.5	2.5
L	3.0	2.5	2.5
H	3.5	3.0	2.5

SET 4 (WVAS 2.0 NMI Min.)

LEAD \ TRAIL	S	L	H
S	2.0	2.0	2.0
L	2.5	2.0	2.0
H	3.0	2.5	2.0

Standards Define Minimum Separations at the Closest Point of Approach

FIGURE 3-1
IFR SEPARATION STANDARDS

system coverage out to the middle marker was considered in Reference 6, but the capacity benefits gained were minimal. Third, saturated traffic is assumed at the arrival fixes, and from the arrival fixes to the runway threshold. This assumption allows assessment of the maximum capacity benefits of the various schemes. Fourth, the lowest altitude for intercepting the glide slope is 3000 feet above ground level. Although arbitrary, this altitude is in the range of current day operations and represents a trade-off between considerations of traffic safety, noise abatement, and minimum required vortex system coverage.

3.3 Spacing Reduction Schemes

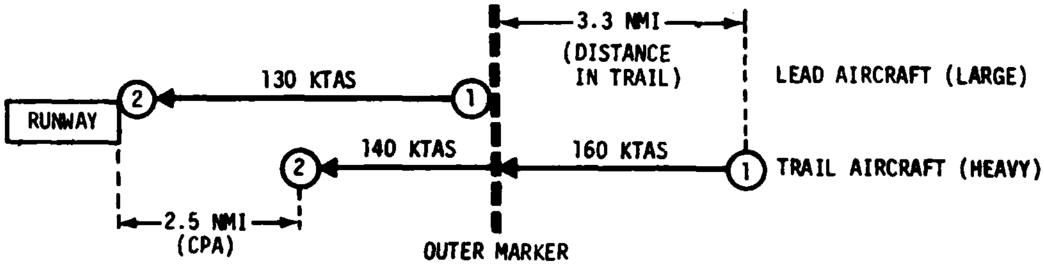
There is considerable flexibility in options available to controllers for maneuvering traffic. Among these options are speed control, vectoring to extend or shorten paths, horizontal and vertical merging as well as traffic redistribution. In implementing a vortex system at an airport for reducing spacing between arriving aircraft, a system which uses procedures which are consistent with those already in use would be highly desirable. The schemes presented in these analyses take elements of procedures already used by controllers and adjust them to allow reduced separations. These schemes are: accordion effect, vertical merging and horizontal merging.

3.3.1 Accordion Effect

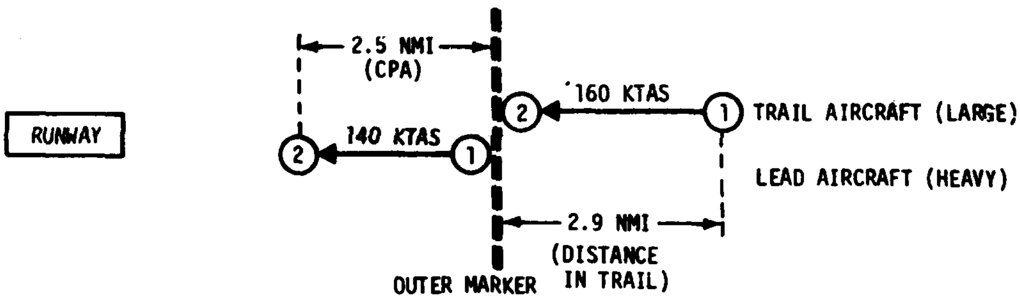
The term "accordion effect" was used in Reference 6 to denote the natural closing which takes place as the lead aircraft slows to its final landing speed. Aircraft are assumed to reduce their speeds at the outer marker. Depending on the speed differential of the two aircraft involved, the closest point of approach (CPA) between the two aircraft may occur at either the trail aircraft at the outer marker or lead aircraft at the runway threshold. The speeds prior to crossing the outer marker are assumed to be 160 knots for all aircraft types. After crossing the outer marker, the final landing speeds of the various aircraft are: small - 120 knots, large - 130 knots, and heavy - 140 knots.

The amount of additional in-trail separation required by the trail aircraft so that the speed differential will result in the desired minimum separation at CPA is illustrated in Figure 3-2 for a 2.5 nmi. minimum standard.

In Figure 3-2 (A), the lead aircraft is a large and the trail is a heavy. The CPA will occur with the lead aircraft at the runway threshold, as the heavy aircraft closes on the slower



A. TRAIL AIRCRAFT FASTER THAN LEAD AIRCRAFT



B. TRAIL AIRCRAFT SLOWER THAN LEAD AIRCRAFT

LEGEND: (1) POSITION OF AIRCRAFT AT BEGINNING OF CLOSURE
(2) POSITION OF AIRCRAFT AFTER CLOSURE
KTAS - KNOTS TRUE AIRSPEED

FIGURE 3-2
EXAMPLES OF COMPUTING CLOSEST POINT OF APPROACH

large aircraft. The distance in-trail required for the heavy aircraft is 3.3 nmi. just prior to the large aircraft crossing the outer marker so that a CPA of 2.5 nmi. will be achieved at the runway threshold. The reverse situation is shown in Figure 3-2 (B). The lead aircraft is now a heavy and the trail is a large. In this case, the CPA occurs with the trail aircraft at the outer marker, because at this point the trail aircraft slows to 130 knots and the lead aircraft (flying at 140 knots) pulls away. The distance in-trail required for the large aircraft is 2.9 nmi. just prior to the heavy aircraft crossing the outer marker.

Using the accordion effect, with vortex system coverage only out to the outer marker, poses an operational constraint of having separations between aircraft satisfying terminal area standards prior to their crossing the outer marker. In Figure 3-2 (B), the separation between a heavy-large pairing would be 5 nmi., instead of 2.9 nmi, and the CPA would be 4.4 nmi. instead of 2.5 nmi. A summary of the achieved separations using the accordion effect and vortex system coverage out to the outer marker is shown in Figure 3-3. For VAS and WVAS 2.5 separations, the minimum separations at CPA are higher than the proposed standards only when the lead aircraft is a heavy aircraft. For WVAS 2.0, however, nearly all of the minimum CPA distances are higher than those shown in Figure 3-1. The net result of the increased separations is that the capacity benefits are not as great as would be realized if the minima shown in Figure 3-1 could be achieved. In order to realize the full potential capacity benefits of a WVAS environment, other schemes are needed.

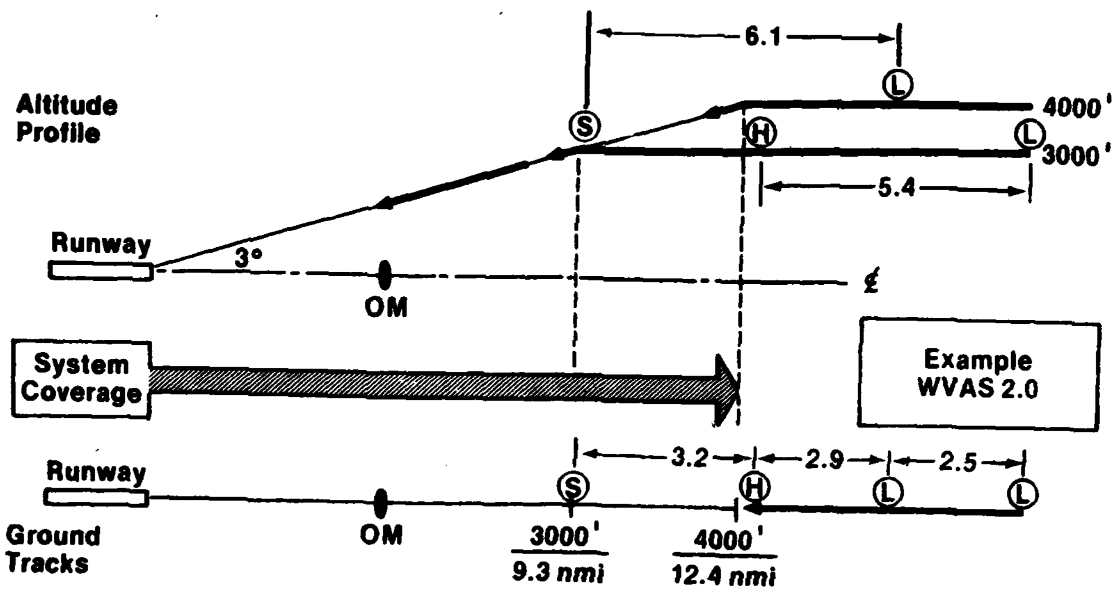
3.3.2 Vertical Merging

Under current operations, controllers routinely insert aircraft into sufficiently large spaces in the arrival traffic stream whenever traffic permits. One method of achieving the desired separations in a vortex system environment under green light conditions is to employ a scheme which would merge two altitude streams in a systematic fashion, merging aircraft alternately from each altitude. The separations between aircraft arriving at the same altitude would allow a gap for inserting an aircraft from the other altitude.

A schematic diagram for achieving reduced spacing on the localizer using vertical merging is presented in Figure 3-4. This scheme merges two streams of aircraft from altitudes of 3000 and 4000 feet above ground level. The vortex system coverage extends out to 12.4 nautical miles from the runway

SEPARATION STANDARD NAME	ACHIEVED SEPARATION AT CLOSEST POINT OF APPROACH				MINIMUM SEPARATION REQUIRED FROM LEAD AIRCRAFT AT OUTER MARKER			
	LEAD	TRAIL S	TRAIL L	TRAIL H	LEAD	TRAIL S	TRAIL L	TRAIL H
TODAY	S	3	3	3	S	4.0	4.2	4.4
	L	4	3	3	L	4.9	3.7	3.9
	H	6	5	4	H	6.7	5.7	4.6
VAS	S	3	3	3	S	4.0	4.2	4.4
	L	3	3	3	L	3.7	3.7	3.9
	H	4.4	4.4	3.5	H	5	5	4
WVAS 2.5	S	2.5	2.5	2.5	S	3.3	3.6	3.8
	L	3	2.5	2.5	L	3.7	3.1	3.3
	H	4.4	4.4	3.5	H	5	5	4
WVAS 2.0	S	2.2	2	2	S	3	3	3.2
	L	2.5	2.4	2.3	L	3.1	3	3
	H	4.4	4.4	3.5	H	5	5	4

FIGURE 3-3
SUMMARY OF ACHIEVED SEPARATIONS USING ACCORDION EFFECT



- **Possible Need for Traffic Segregation**

FIGURE 3-4
SPACING REDUCTION USING VERTICAL MERGING

threshold, to the point at which the top altitude stream intercepts the glide slope and begins descent. The area between 9.3 and 12.4 nautical miles is an area of additional concern because aircraft from 4000 feet will be descending to 3000 feet and there may be possible interaction of desending vortices with aircraft at the lower altitude. This potential problem will need to be considered in a definition of a vortex avoidance system which will allow use of this vertical merging scheme.

An example of an arrival stream in the sequence small-heavy-larger-large is also shown in Figure 3-4. In this example, the heavy aircraft is placed at the lower altitude and the small aircraft is placed at the higher altitude to minimize the probability of a hazardous vortex encounter between heavy-large, heavy-small, and large-small pairs.

The minimum separations required between in-trail aircraft outside the outer marker are shown in Figure 3-5. (Note: The aircraft are assumed to slow to their final landing speed at the outer marker.) The separations achieved at the closest point of approach after the aircraft have slowed to their respective final airspeeds are also shown. All the achieved separations in Figure 3-5 are the same as the those which were set as a goal in Figure 3-1. The smallest separation between aircraft at the same altitude would occur in the arrival sequence large-heavy-heavy in which the separation between the large and the second heavy would be 5 nautical miles.

3.3.3 Horizontal Merging

Another method of achieving the desired reduced separations in a vortex system environment is to employ a scheme which would merge two coaltitude streams. A schematic diagram for achieving reduced spacing on the localizer using horizontal merging is presented in Figure 3-6. This scheme merges two coaltitude streams at 3000 feet above ground level. One stream is arriving straight-in on the localizer. The other stream merges from the base leg in the following manner: (1) the aircraft turns to intercept the localizer at 30°, (2) the aircraft flies straight and level for one nautical mile, (3) the aircraft turns onto the localizer course, and (4) the aircraft flies straight and level for one nautical mile prior to intercepting the glide slope. The vortex system coverage required for this scheme is 11.7 nautical miles along the localizer course and also covers the triangular area during the aircraft's turn from base leg onto the localizer. The width of coverage from the localizer course to the start of turn from the base leg is one nautical mile.

SEPARATION STANDARD NAME	ACHIEVED SEPARATION AT CLOSEST POINT OF APPROACH				MINIMUM SEPARATION REQUIRED FROM LEAD AIRCRAFT AT OUTER MARKER			
	LEAD	TRAIL S	TRAIL L	TRAIL H	LEAD	TRAIL S	TRAIL L	TRAIL H
TODAY	S	3	3	3	S	4.0	4.2	4.4
	L	4	3	3	L	4.9	3.7	3.9
	H	6	5	4	H	6.7	5.7	4.6
VAS	S	3	3	3	S	4.0	4.2	4.4
	L	3	3	3	L	3.7	3.7	3.9
	H	4	3	3	H	4.6	3.4	3.4
WVAS 2.5	S	2.5	2.5	2.5	S	3.3	3.6	3.8
	L	3	2.5	2.5	L	3.7	3.1	3.3
	H	3.5	3	2.5	H	4	3.4	2.9
WVAS 2.0	S	2	2	2	S	2.7	3	3.2
	L	2.5	2	2	L	3.1	2.5	2.7
	H	3	2.5	2	H	3.4	2.9	2.3

FIGURE 3-5
SUMMARY OF ACHIEVED SEPARATIONS USING VERTICAL MERGING

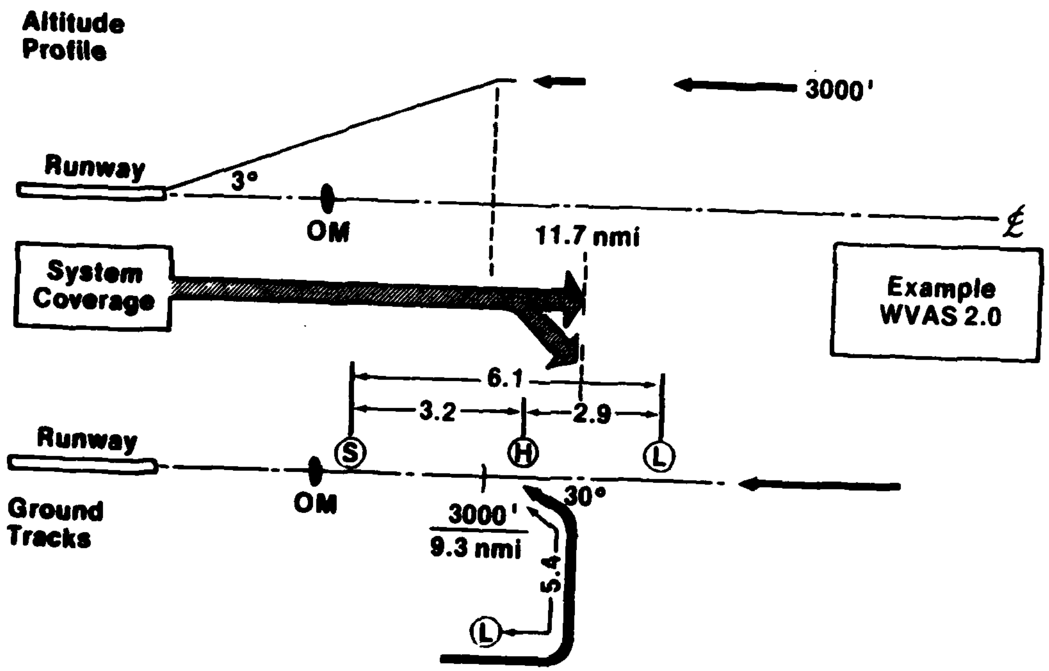


FIGURE 3-6
SPACING REDUCTION USING HORIZONTAL MERGING

The minimum separations required between in-trail aircraft outside the outer marker for vertical merging are shown in Figure 3-5. These separations as well as the achieved separations at closest point of approach for horizontal merging are the same as those for the vertical merging scheme with the exception of WVAS 2.0 heavy-heavy pairing. This exception results from the air traffic control constraint that two aircraft, one on the localizer and one at the turn from baseleg, must be at least three miles apart when the aircraft from base leg turns to intercept the localizer. When both aircraft are established on the localizer, they will be 2.4 nautical miles apart, which is the smallest separation that can be achieved at the outer marker. Thus, for horizontal merging, the WVAS 2.0 heavy-heavy pairing will have a separation at closest point of approach of 2.1 nmi. resulting from a separation of 2.4 nmi. at the outer marker. A 2.0 nmi. spacing for heavy-heavy pairing can be achieved by extending the coverage by 3.0 nmi.

3.4 Comparison of Schemes

Comparisons of the three spacing reduction schemes outlined in the previous sections are presented in Tables 3-1 and 3-2. Table 3-1 shows a summary of the design tradeoff considerations between the vortex system coverage required for a particular scheme and the scheme's capability of achieving the minimum IFR separation standards for final approach previously defined in Figure 3-1. The scheme's ability to achieve these standards translates into higher capacity benefits. The accordion effect requires vortex system coverage to the outer marker. Airport design standards specify that the outer marker may be located 3.5 to 6 nautical miles from the runway threshold (Reference 9). The accordion effect cannot achieve the IFR separation standards for VAS, WVAS 2.5 or WVAS 2.0. On the other hand, both vertical and horizontal merging can achieve the IFR separation standards. The vortex system coverage for the vertical merging scheme is 12.4 nautical miles with a 1000 feet vertical spread required when the aircraft on the top altitude intercepts the glide slope. At 9.3 nautical miles, the vertical spread becomes zero. The horizontal merging scheme requires 11.7 nautical miles of system coverage with a one nautical mile spread required when the aircraft on the base leg turns to intercept the localizer (See Figure 3-6). At 10.3 nautical miles, the horizontal spread becomes zero.

TABLE 3-1

SUMMARY OF TRADEOFF BETWEEN VORTEX SYSTEM COVERAGE REQUIREMENT AND CAPABILITY OF ACHIEVING REQUIRED AIRCRAFT SEPARATION

SPACING REDUCTION SCHEME	CAN SCHEME ACHIEVE IFR SEPARATION STANDARDS FOR FINAL APPROACH (FROM FIGURE 3-1)	DISTANCE FROM RUNWAY THRESHOLD REQUIRED TO BE UNDER SYSTEM COVERAGE
ACCORDION EFFECT	NO	UP TO OUTER MARKER (3.5 TO 6 NMI)
VERTICAL MERGING	YES	12.4 NMI (1000' VERTICAL SPREAD)
HORIZONTAL MERGING	YES	11.7 NMI (1 NMI HORIZONTAL SPREAD)

Table 3-2 provides a comparison of the operational advantages and disadvantages of the proposed schemes. The advantage of using the accordion effect is that there is no change in operational procedures other than close adherence of the aircraft types to their respective final approach and final landing speed profiles. The disadvantage of this scheme is that it does not achieve the full potential capacity benefits of the reduced spacing on final approach. Both the vertical merging and horizontal merging schemes are capable of achieving the full potential capacity benefits.

The vertical merging scheme has the advantages of having straight-in approach paths and unidirectional vortex system coverage. The straight-in approach path allows the controller to visualize the relative spacing between aircraft and their arrival sequence on the plan view (CRT) display. One disadvantage of the vertical merging scheme is that parallel runway operations would require four altitude streams. The use of four altitudes would extend the vortex system coverage substantially. Another disadvantage is the possible need for segregation of traffic. Depending on the vortex behavior in the descent area where aircraft from the top altitude stream have intercepted the glide slope and are descending while aircraft on the lower altitude stream are still maintaining their altitude, heavy aircraft may have to be restricted to the lower altitude for safe operations. Small aircraft may also have to be restricted to the upper altitude for the same reason.

The horizontal merging scheme has the advantage of being compatible with proposed automated metering and spacing geometries. There are a number of disadvantages, however. This scheme requires accuracy of turning procedures near the merge point to avoid unsafe overshoot conditions. It requires a wide angle of coverage near the merge point (one nautical mile width). This scheme uses multiple low level approach paths near the airport which may be in conflict with desired noise abatement procedures. There is also a possible sensitivity to vortex movements due to crosswind. This perhaps can be accounted for by an adjustment in the system's algorithms.

A selection between the two schemes will depend on the specific airport operations. It may be advantageous to combine the two schemes, especially for parallel runway operations. Applications of these schemes to Atlanta and O'Hare are discussed in the following sections.

TABLE 3-2

COMPARISON OF OPERATIONAL ADVANTAGES AND DISADVANTAGES OF PROPOSED SCHEMES

SPACING REDUCTION SCHEME	ADVANTAGES	DISADVANTAGES
ACCORDION EFFECT	NO CHANGE IN OPERATIONAL PROCEDURES	DOES NOT ACHIEVE FULL POTENTIAL BENEFITS
VERTICAL MERGING	STRAIGHT-IN APPROACH PATH UNIDIRECTIONAL VORTEX SYSTEM COVERAGE	POSSIBLE NEED FOR SEGREGATION OF TRAFFIC PARALLEL OPERATIONS REQUIRE FOUR ALTITUDE STREAMS
HORIZONTAL MERGING	COMPATIBLE WITH PROPOSED AUTOMATED METERING AND SPACING GEOMETRIES	REQUIRES ACCURACY OF TURNING PROCEDURES NEAR MERGE POINT WIDER ANGLE OF COVERAGE REQUIRED NEAR MERGE POINT USE OF MULTIPLE LOW LEVEL APPROACH PATHS NEAR AIRPORT POSSIBLE SENSITIVITY TO VORTEX MOVEMENTS DUE TO CROSSWINDS

4. ATLANTA OPERATIONS

Described in this section is an analysis of the operational feasibility of the use of WVAS operations and merging schemes for Atlanta Hartsfield International Airport. This includes an analysis of transitioning between different sets of separation standards as well as an estimate of the capacity benefits at Atlanta that would result from the use of reduced separations on final approach.

4.1 Terminal Area Operations

Atlanta has three east-west runways, as shown in Figure 4-1. Runway 8/26 is furthest north and closest to the terminal. Runway 9L/27R is 4400 feet south of 8/26; Runways 9R/27L and 9L/27R are 1050 feet apart. Runway 9R/27L is used almost exclusively for arrivals while 9L/27R is used almost exclusively for departures. Runway 8/26 is used for both arrivals and departures. Because of the similarity in east and west flight operations and procedures, only consideration of east operations is presented in the following description and analysis.

Arrival and departure vector routes for east operations at Atlanta are shown in Figure 4-2. A complete description of ground and airborne scenarios is given in Reference 6. Arrivals to runway 26 are fed primarily from the Dalas and Logen fixes while those to runway 27L are fed primarily from Tiroe and Husky. If simultaneous ILS approaches are used, aircraft approaching runway 27L must turn on final approach at an altitude of 1000 feet below aircraft on approach to runway 26. Simultaneous departures are authorized on runway 26 and 27R. Departures are restricted in climb to 10000 feet altitude until they are clear of decending arrival traffic from Dalas and Tiroe. Arrival traffic from these fixes are restricted above 11000 feet until past the departure traffic headed north or south.

4.2 Application of Merging Schemes

A design goal in this study has been to limit procedural changes in current operational practices for implementation of WVAS operations. In the preceeding section, a description of current operational procedures at Atlanta was presented. In this section, these procedures are modified to allow implementation of vertical and horizontal merging schemes. Figures 4-3 and 4-4 show proposed operational procedures for Atlanta using horizontal and vertical merging schemes. Atlanta is at an elevation of 1026 feet. These merging schemes are based on an

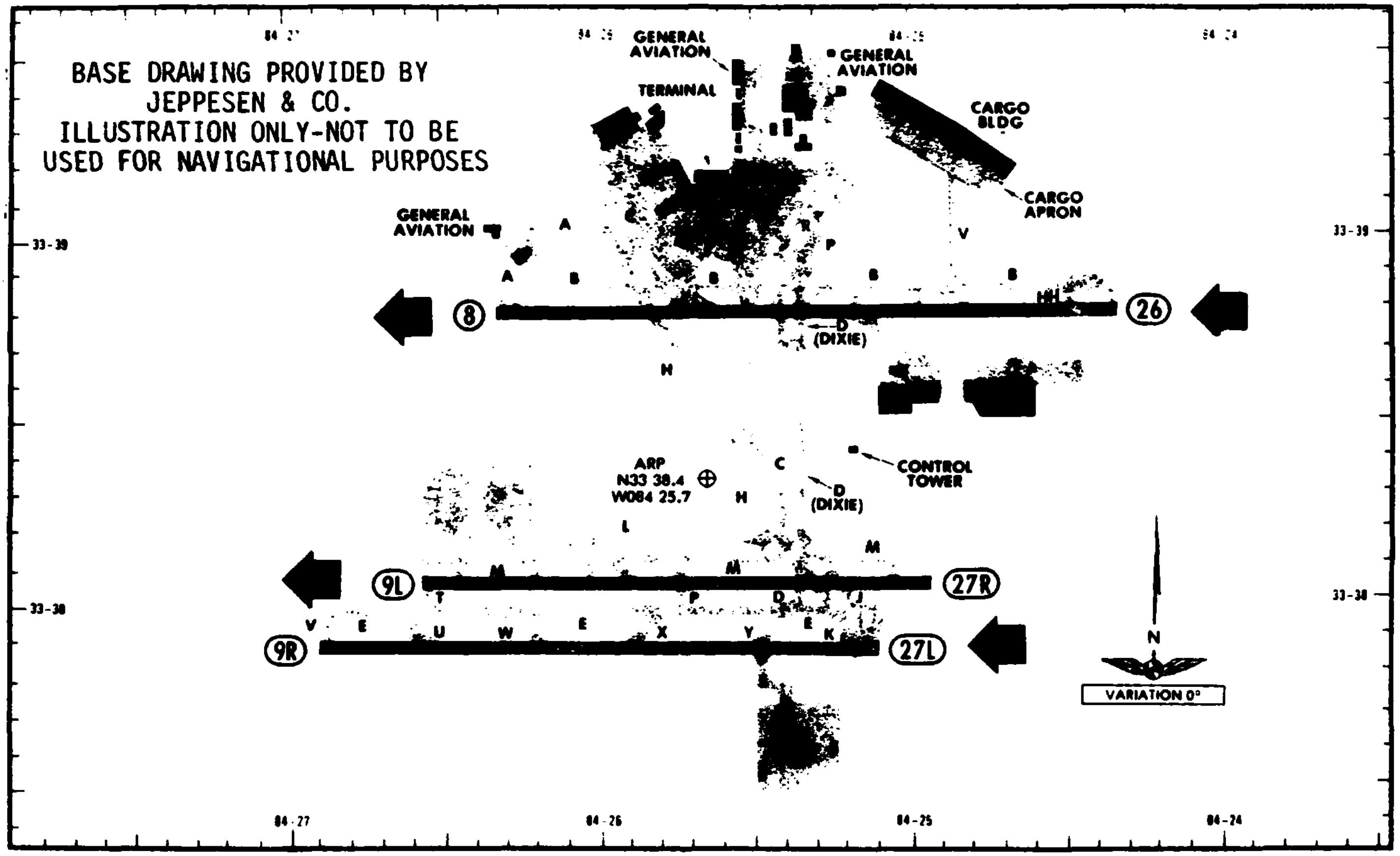


FIGURE 4-1
ATLANTA HARTSFIELD INTERNATIONAL AIRPORT LAYOUT

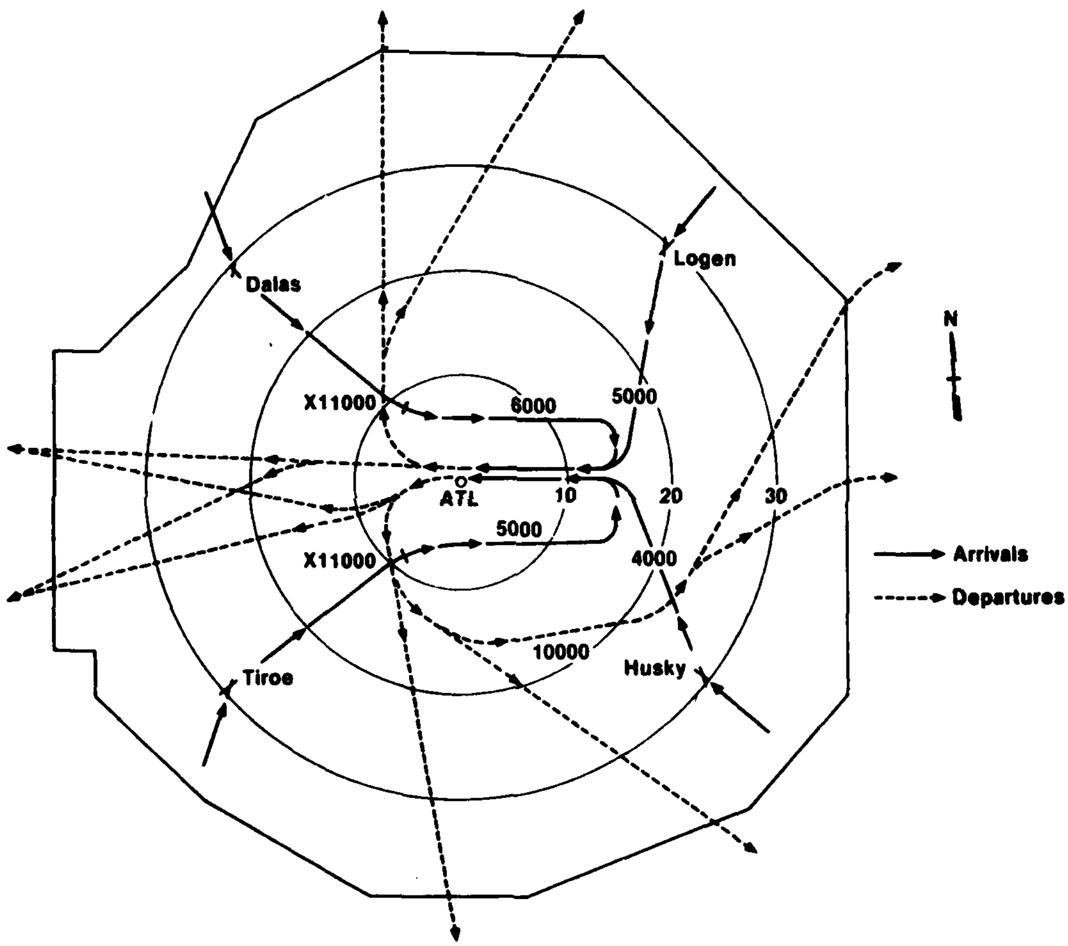


FIGURE 4-2
ARRIVAL/DEPARTURE VECTOR ROUTES FOR ATLANTA

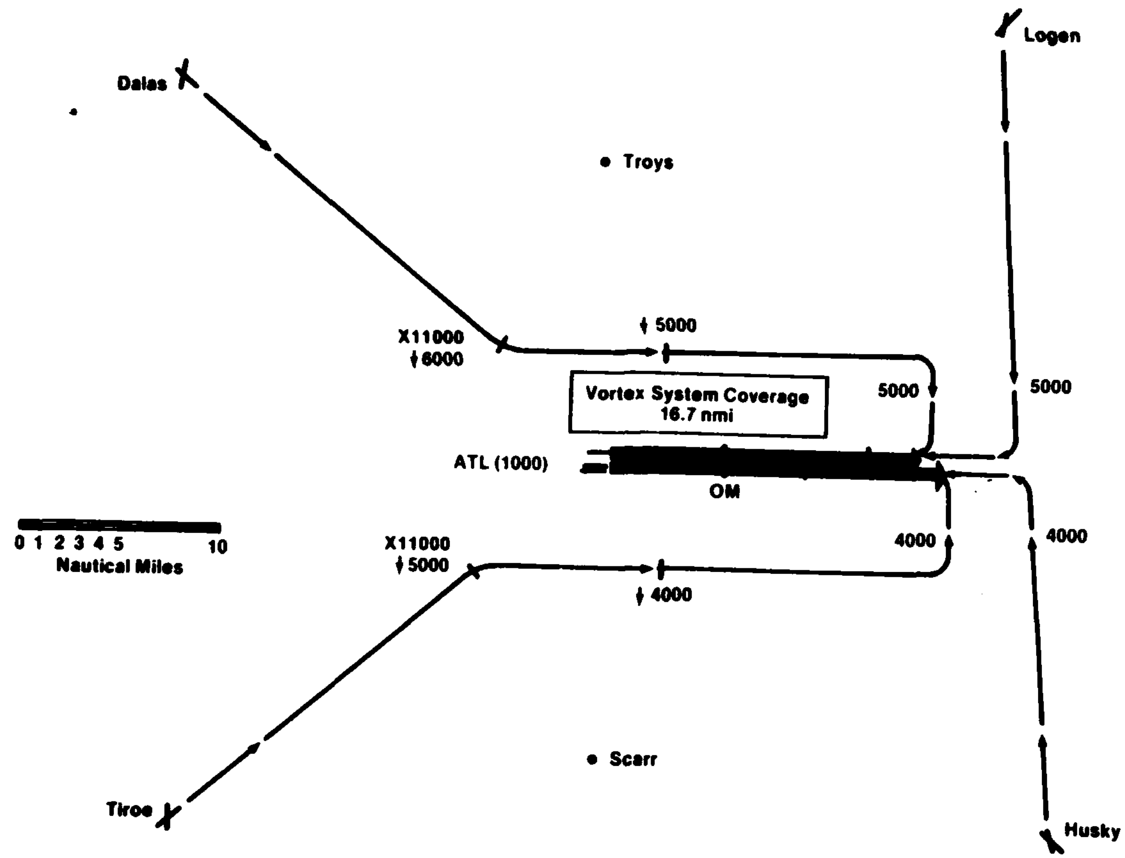


FIGURE 4-3
PROPOSED OPERATIONAL PROCEDURES FOR ATLANTA
USING HORIZONTAL MERGING

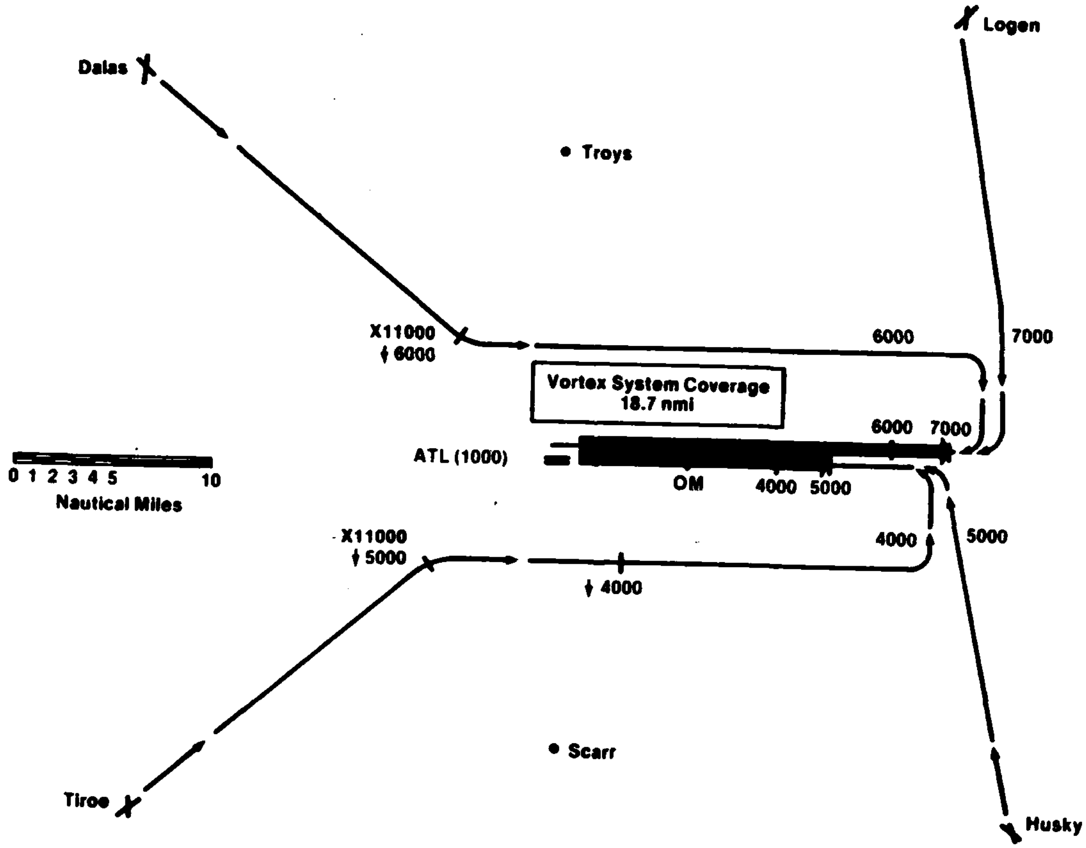


FIGURE 4-4
PROPOSED OPERATIONAL PROCEDURES FOR ATLANTA
USING VERTICAL MERGING

assumed minimum altitude differential of approximately 3000 feet between ground elevation and the glide slope interception altitude. Thus, the lowest arrival altitude prior to intercepting the glide slope is 4000 feet. The horizontal merging scheme needs a vortex system coverage of 16.7 nautical miles, while the vertical merging scheme needs 18.7 nautical miles of coverage. The coverage for the vertical merging scheme is the result of using 6000 and 7000 feet as merging altitudes on the north sector. This could be reduced to 15.6 nautical miles if altitudes of 5000 and 7000 feet were used to merge aircraft in the north sector and 4000 and 6000 feet were used to merge aircraft in the south sector.

An alternative to using either horizontal or vertical merging schemes exclusively is to use a hybrid scheme involving horizontal merging on one half of the airport and vertical merging on the other. No major advantage is attributed to the hybrid scheme other than it allows a particular controller to use his preferred method of merging. The disadvantage is that the hybrid scheme does not have uniformity of procedures.

4.3 Transitions To and From Reduced Spacing

The sections thus far have addressed schemes for achieving reduced separation standards for vortex system operations. Two questions arise concerning the transition effects of changing from one standard to another. These are (1) how can changes in interarrival spacing be accommodated when the standards are changed, and (2) how much warning time is required for smooth transitioning?

4.3.1 Missed Approach Analysis

When the vortex system designates that the separation standards should be decreased, the transition becomes one of increasing the arrival rate over the arrival fixes. The transition is a smooth one because the aircraft gradually decrease their interarrival spacing and no safety problems are encountered. When the vortex system designates that the separation standards should be increased, the transition becomes more complex because aircraft already in the arrival stream must either be held in a holding pattern, sent around for another approach, or slowed down to allow for large interarrival spacing. Now the concerns include which aircraft should be sent around, how much can individual aircraft be slowed down, and what strategies should be employed to achieve the desired spacing.

One solution is to send every other aircraft around for another approach while allowing the others to land. This solution is easy to implement in that the controller need not know the composition of the arrival stream. A second solution is to use a combination of go-arounds and speed control to allow the greatest number of aircraft already in the arrival stream to land. This second solution allows the least amount of delay and is the most fuel conservative. However, the controller's workload must increase to handle the unique combination of go-arounds and speed commands which will accomplish the desired strategy. Some automation aids, such as terminal Metering and Spacing, may be necessary to handle the increased workload.

Figure 4-5 shows examples of strategies which might be used for an arrival stream in which 5 aircraft are situated between the outer marker and the turn to base leg. For this analysis, the following assumptions are made:

(1) arrival aircraft inside the outer marker are allowed to land.

(2) aircraft situated between the outer marker and the turn to base leg (within 15 nautical miles of the outer marker) are considered for a possible missed approach.

(3) aircraft in the arrival stream greater then 15 nmi from the outer marker can use an extended downwind or holding pattern to absorb the delay required for increased interarrival spacing.

(4) speed control alone is used to adjust spacing, increasing speed as much as 20 knots or decreasing as much as 10 knots.

(5) aircraft which are selected to execute a missed approach are cleared expeditiously and have no further impact on the spacing of the aircraft following them in the arrival stream.

(6) the amount by which the interarrival spacing can be increased or decreased is based on the average separation spacing (this concept is explained in Appendix A).

In Figure 4-5, for strategy 1, with aircraft 2 executing a missed approach, aircraft 3 increasing its air speed by 10 knots, and aircraft 6 elongating its path on an extended downwind, an increase of .7 nautical miles can be obtained

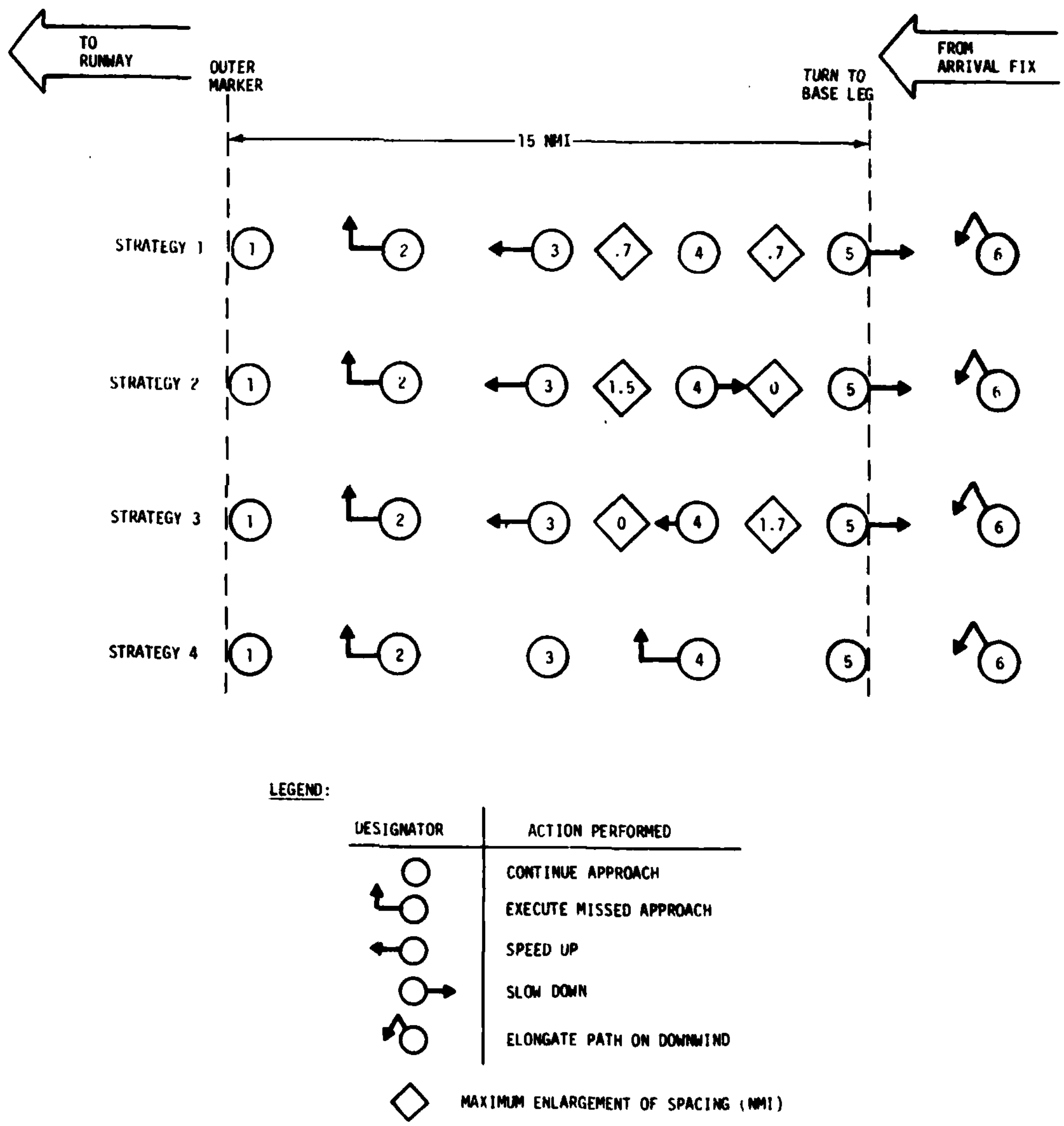


FIGURE 4-5
EXAMPLES OF STRATEGIES USED TO INCREASE INTERARRIVAL SPACING

between aircraft 3 and 4 and also between 4 and 5. For strategy 2, the maximum increase in interarrival spacing is 1.5 nmi. This spacing is achieved by not allowing any increase in spacing between aircraft 4 and 5. Strategy 3 is similar in concept. These three strategies illustrate methods by which spacings can be adjusted by allowing only one missed approach. Strategy 4 allows 2 missed approaches. This strategy must be used if the combined desired increase in spacing between aircraft 3 and 5 is more than 1.4 nmi. and the individual required changes in spacing between aircraft 3 and 4 and aircraft 4 and 5 is greater than .7 nmi., or (2) if the desired spacing between aircraft 3 and 4 is more than 1.5 nmi. and there is no change required between aircraft 4 and 5, or (3) if the desired spacing between aircraft 4 and 5 is more than 1.7 nmi. and there is no change required between aircraft 3 and 4. The derivation of these limits is shown in Appendix A.

Using similar strategies for adjusting interarrival spacing the number of missed approaches for a given aircraft sequence is minimized. The probabilities that certain numbers of missed approaches will occur if separation standards are changed are shown for Atlanta in Table 4-1. The derivation of these probabilities is shown in Appendix A. Today's mix of aircraft at Atlanta is estimated to be 13% heavy, 73% large and 14% small. A nominal warning time of 2.5 minutes is assumed so that aircraft between the outer marker and the runway are allowed to land. For example, consider a change in separation standards from WVAS 2.5 standard to today's standard. With the use of strategies outlined in Figure 4-5 to adjust interarrival spacing, 57% of the time there would be 1 missed approach and 43% of the time there would be 2 missed approaches. As the changes in separation spacing standards become more severe, such as from WVAS 2.0 to today's, a larger number of missed approaches will occur more often.

4.3.2 Warning Time Requirements

What would happen if the warning time for an impending separation standard change were to be increased? Depending on the aircraft's speed profile, warning time can be translated into distance from the runway threshold and vice versa.

The following speed profile was used in computing the warning times in Table 4-2: inside the outer marker - 120 knots, outside the outer marker on the localizer - 170 knots (an average between 160 and 180), on the base leg - 180 knots, and outside the base leg - 210 knots. These airspeeds are estimates of the aircraft's performance and the warning times are computed

TABLE 4-1
PROBABILITY OF MISSED APPROACHES RESULTING
FROM CHANGE IN SEPARATION STANDARD
AT ATLANTA

ORIGINAL STANDARD	NEW STANDARD		
	TODAY'S	VAS	WVAS 2.5
WVAS 2,0 6AC*	(2)** 86% (3) 14%	(2) 100%	(1) 100%
WVAS 2.5 5AC*	(1) 57% (2) 43%	(0) 7% (1) 93%	
VAS 4AC*	(0) 40% (1) 57% (2) 3%		

*NUMBER OF AIRCRAFT CONSIDERED FOR POSSIBLE MISSED APPROACH

**NUMBERS IN PARENTHESES INDICATE NUMBER OF MISSED APPROACHES

INTERPRETATION: WHEN THE SPACING STANDARD CHANGES FROM WVAS 2.0 TO TODAY'S, FOR THE 6 AIRCRAFT CONSIDERED, 86% OF THE TIME THERE WILL BE 2 MISSED APPROACHES AND 14% OF THE TIME THERE WILL BE 3 MISSED APPROACHES.

TABLE 4-2

EFFECT OF VARIOUS ADVANCE WARNING TIMES OF CHANGE IN AIRCRAFT SPACING FOR ATLANTA

AIRCRAFT ADMITTED WITH ORIGINAL SPACING (NMI TO RUNWAY)	AMOUNT OF ADVANCE WARNING OF CHANGE IN SEPARATION STANDARDS (MINUTES)	EFFECT
INSIDE OUTER MARKER (5)	2.5	HIGH PROBABILITY OF ONE OR TWO MISSED APPROACHES (AS PREVIOUS CHART)
ON LOCALIZER (15)	6.0	LOW PROBABILITY OF ONE MISSED APPROACH
ON BASE LEG OR LOCALIZER (20)	7.7	NO MISSED APPROACHES. LARGE EXTENSION OF DOWNWIND AREA
FROM CLOSEST APPROACH FIX (35)	12.0	NO MISSED APPROACHES. SMALL EXTENSION OF DOWNWIND AREA
FROM FARTHEST APPROACH FIX (60)	19.1	NO MISSED APPROACHES. STABLE TRANSITION

from these estimates. The effect of changing standards with a minimum warning time of approximately 2.5 minutes resulted in various consequences as presented in Table 4-2. Qualitatively, the effect of changing the standards can be summarized that there is a high probability of one or two missed approaches with increased separation spacing with a 2.5 minute warning time. With a warning time of 6 minutes for which all aircraft on the localizer are allowed to land, there will be a low probability of one missed approach from those aircraft on the base leg. With a warning time of about 7.7 minutes for which all aircraft on base leg or localizer are allowed to land, there will be no missed approaches; however, there will be a large extension of the downwind area because aircraft already in the arrival stream must be delayed by extending their flight paths to accommodate the enlarged interarrival spacing. With a warning time of about 12 minutes, there will be no missed approaches and a slight extension of the downwind area. With a warning time of about 19.1 minutes, there will be no missed approaches and a stable transition from one standard to another will occur.

4.4 Capacity Impacts

The study thus far has concentrated on the feasibility assessment of achieving reduced separations permissible under green light conditions. This section deals with the capacity impacts of using the different merging schemes and their comparison to the capacity estimates obtained by using today's standard with today's mix of aircraft (14% small, 73% large, and 13% heavy).

Table 4-3 presents a summary of the percent increase in runway capacity obtained from the MITRE capacity model (Reference 10) with inputs taken from Reference 4. The input values are given in Appendix B.

Table 4-3(B) assumes 50% arrivals for Atlanta using an arrival-departure runway for the north runway and a dual runway system for the south, whereas Table 4-3(A) is valid for 100% arrivals only. The 100% arrival configuration shows the effects of implementing the various merging schemes without consideration for departure-departure or arrival-departure spacings. The accordion effect provides capacity increases (over using today's standard) ranging from 4.4% for VAS to 28.9% for WVAS 2.0. Using vertical or horizontal merging provides capacity increases ranging from 7.9% for VAS to 44.0% for WVAS 2.0. The additional benefit from using vertical or horizontal merging instead of using the accordion effect provides increased capacity from 3.5% for VAS to 15.1% for WVAS 2.0.

TABLE 4-3

CAPACITY BENEFITS FOR ATLANTA

(A) CAPACITY BENEFITS FOR ATLANTA
USING VORTEX SYSTEM SEPARATIONS
ASSUMING 100% ARRIVALS

SEPARATION STANDARD NAME	% INCREASE IN RUNWAY CAPACITY	
	ACCORDION EFFECT	VERTICAL OR HORIZONTAL MERGING
VAS	4.4	7.9
WVAS 2.5	14.6	19.3
WVAS 2.0	28.9	44.0

(B) CAPACITY BENEFITS FOR ATLANTA
USING VORTEX SYSTEM SEPARATIONS
ASSUMING 50% ARRIVALS

SEPARATION STANDARD NAME	% INCREASE IN RUNWAY CAPACITY	
	ACCORDION EFFECT	VERTICAL OR HORIZONTAL MERGING
VAS	3.4	3.8
WVAS 2.5	10.0*	13.0
WVAS 2.0	19.0	23.0

*IF NO DEPARTURE/DEPARTURE SPACING REDUCTION WERE AVAILABLE, CAPACITY BENEFITS WOULD BE:

WVAS 2.5	7.4	7.9
WVAS 2.0	13.8	13.9

The computed capacity benefits resulting from using the reduced spacing schemes are decreased when departure-departure and arrival-departure spacings are considered since the north runway at Atlanta is an arrival-departure runway. The computed capacity benefits for the south independent dual runway are unaffected by this consideration. The accordion effect now provides capacity increases ranging from 3.4% for VAS to 19.0% for WVAS 2.0. Using vertical or horizontal merging provides capacity increases ranging from 3.8% for VAS to 23.0% for WVAS 2.0. The additional benefit from using vertical or horizontal merging instead of using the accordion effect provides increased capacity from 0.4% for VAS to 4.0% for WVAS. Thus, for Atlanta, the differences in capacity benefits resulting from using the more complicated vertical or horizontal merging schemes instead of using the accordion effect are decreased because of the restricting effect of the north arrival-departure runway.

The vortex system model used to calculate these benefits assumes departure-departure spacings (in seconds) of 60/90/120 for VAS, 60/60/90 for WVAS 2.5, and 60/60/60 for WVAS 2.0. If no departure-departure spacing reduction were available, i.e., 60/90/120 separations were assumed for all cases, there would virtually be no increased benefit from using the more complicated vertical or horizontal merging schemes.

5. O'HARE OPERATIONS

Described in this chapter is the analysis of the operational feasibility of the use of WVAS type operations and merging schemes for Chicago O'Hare International Airport. This includes an analysis of transitioning between different sets of separation standards as well as an estimate of the capacity benefits at Chicago O'Hare that would result from the utilization of reduced separations standards on final approach.

5.1 Terminal Area Operations

The runway and taxiway layout of Chicago O'Hare is shown in Figure 5-1. The particular configuration chosen for the feasibility analysis is arrivals on runways 27L and 27R and departures on runways 32L and 32R. These are indicated by arrows in Figure 5-1. Aircraft departing on runway 32L roll from Taxiway 1, and are therefore independent of arrivals on runway 27L. Furthermore, operations on the north side (27R and 32R) are independent of operations on the south side (27L and 32L). The configuration which was chosen can therefore be decomposed into three components: an arrivals-only runway (27L), a departures-only runway (32L), and an intersecting pair of runways handling both arrivals and departures (27R/32R).

Figure 5-2 illustrates the nominal arrival and departure routes for the selected IFR configuration for O'Hare (667 feet MSL), as used today. These procedures are taken from Reference 11. The south arrivals, i.e., those from Vains, CGT (Chicago Heights) and Plant, are handed over to the TRACON at 7000 feet MSL or higher. The three routes are merged at 5000 feet MSL and the aircraft on this route intercept the glide slope at the same altitude. North arrivals from Farmm and Base are also at 7000 feet MSL or higher on entering the TRACON control. The aircraft from MKE (Milwaukee) are at 6000 feet MSL. The three north arrival routes merge at about 6000 feet MSL and then descent to and level at 4000 feet before making the final turn to intercept the localizer. North-bound and east-bound departures from 32R and south-bound departures from 32L must remain at 5000 feet or below until clearing the arrival paths, as shown in Figure 5-2, and then climb to 24,000 feet MSL or cruise altitude, whichever is lower. West-bound departures from 32L have a direct, unrestricted climb to 24,000 feet MSL or cruise altitude. Minimum perturbation of today's procedures is a desirable goal in the design of operational procedures to attain closer WVAS type spacings on final approach while maintaining terminal area spacings prior to intercepting WVAS coverage.

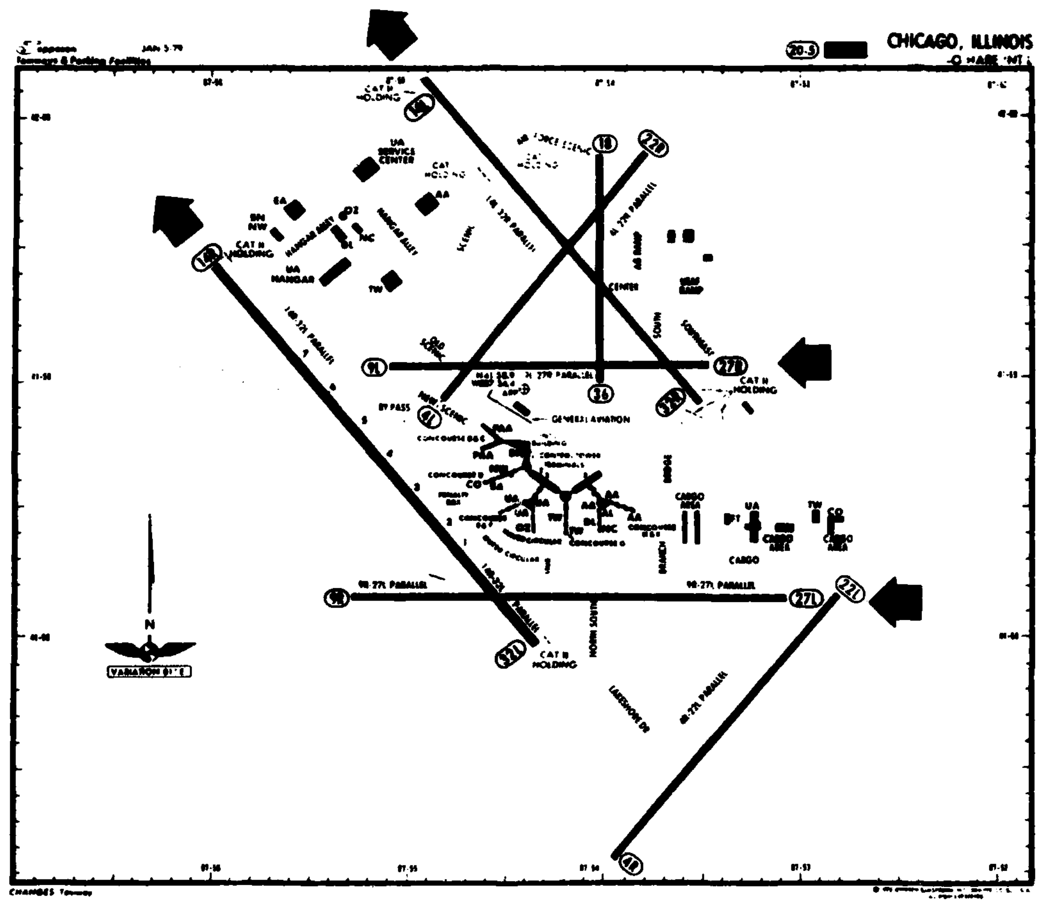


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FIGURE 5-1
CHICAGO O'HARE INTERNATIONAL AIRPORT LAYOUT

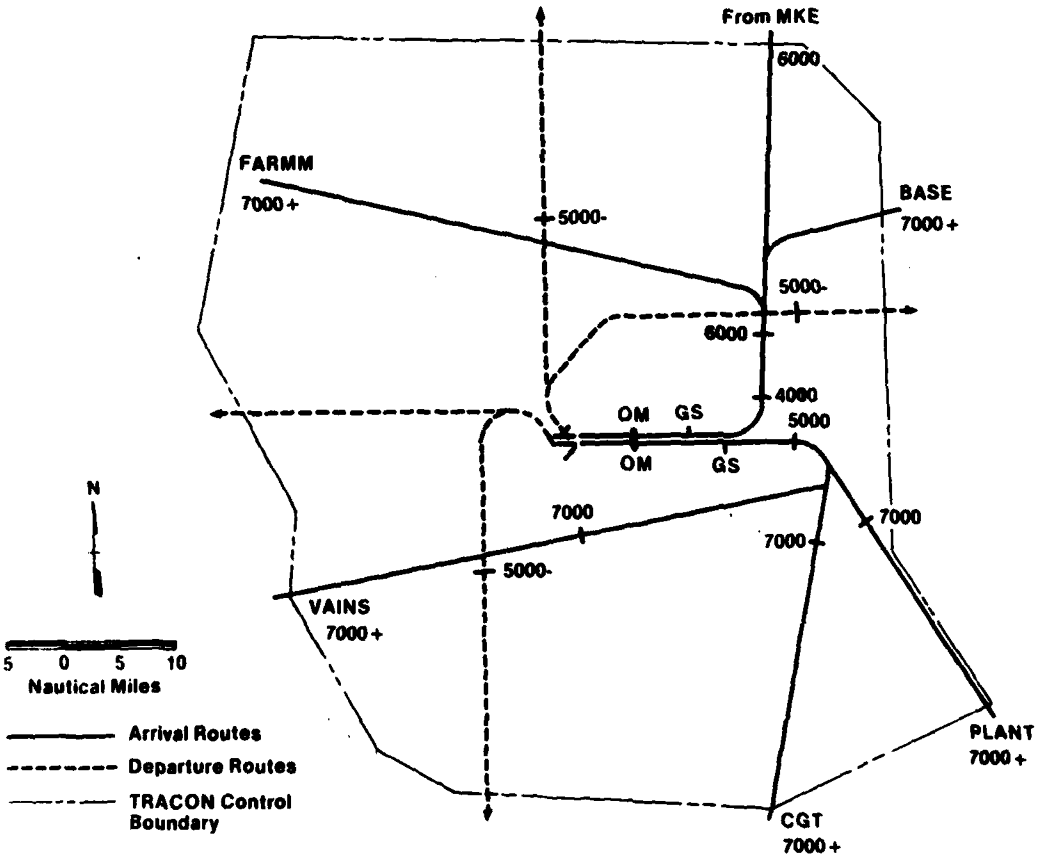

FIGURE 5-2
ARRIVAL/DEPARTURE VECTOR ROUTES FOR O'HARE

5.2 Application of Merging Schemes

The general merging schemes described in Chapter 3 were applied to the specific case of operations at O'Hare using the selected runway configuration (arrivals on 27L and 27R, departures on 32L and 32R).

5.2.1 Horizontal Merging

The horizontal merging scheme is designed around the concept of merging two streams into one, with WVAS coverage extending to the merge point. However, each of the two arrival runways is fed from three fixes: Farmm, MKE, and Base feed runway 27R; CGT, Vains, and Plant feed runway 27L. Consequently, the first procedure is to merge the six streams into four. In Figure 5-3 this is accomplished by merging traffic from Farmm and MKE into one stream, as well as traffic from Vains and CGT. This choice is due to the fact that most of the traffic comes from Base and Plant. However, for both the north and south sides, it is possible to achieve equal loading on each of the two traffic streams, maintaining full capacity, independent of the instantaneous flow rates from each fix.

The resulting two steams on the north side are merged at 4000 feet MSL, while the two streams on the south side are merged at 5000 feet. These could be reversed, but there does not seem to be any advantage or disadvantage to doing so. Altitude profiles for the arrivals are kept as similar to today's procedures as possible, the only differences being arrivals from CGT and Plant starting their descents from 7000 feet to 5000 feet slightly earlier under the horizontal merging scenario. Departure paths are the same with horizontal merging, except east-bound departures from runway 32R must maintain 5000 feet or less for an additional five miles.

Localizer intercepts are dictated by stabilization requirements and vertical separation requirements. The 5000 feet stream (south side) must be stabilized on the localizer at the point where the glide slope is intercepted. For this reason, the localizer intercept for the close 5000 foot stream is three miles out from the glide slope intercept. The 4000 foot stream aircraft must be stabilized on the localizer at the point where vertical separation of 1000 feet is lost. This occurs at the 5000 foot stream glide slope intercept. Consequently the close 4000 foot stream intercepts the localizer three miles out from the 5000 foot glide slope intercept or about six miles from its own glide slope intercept. Far streams for both 4000 foot and 5000 foot traffic intercept the localizer about three miles out from the close stream localizer intercepts.

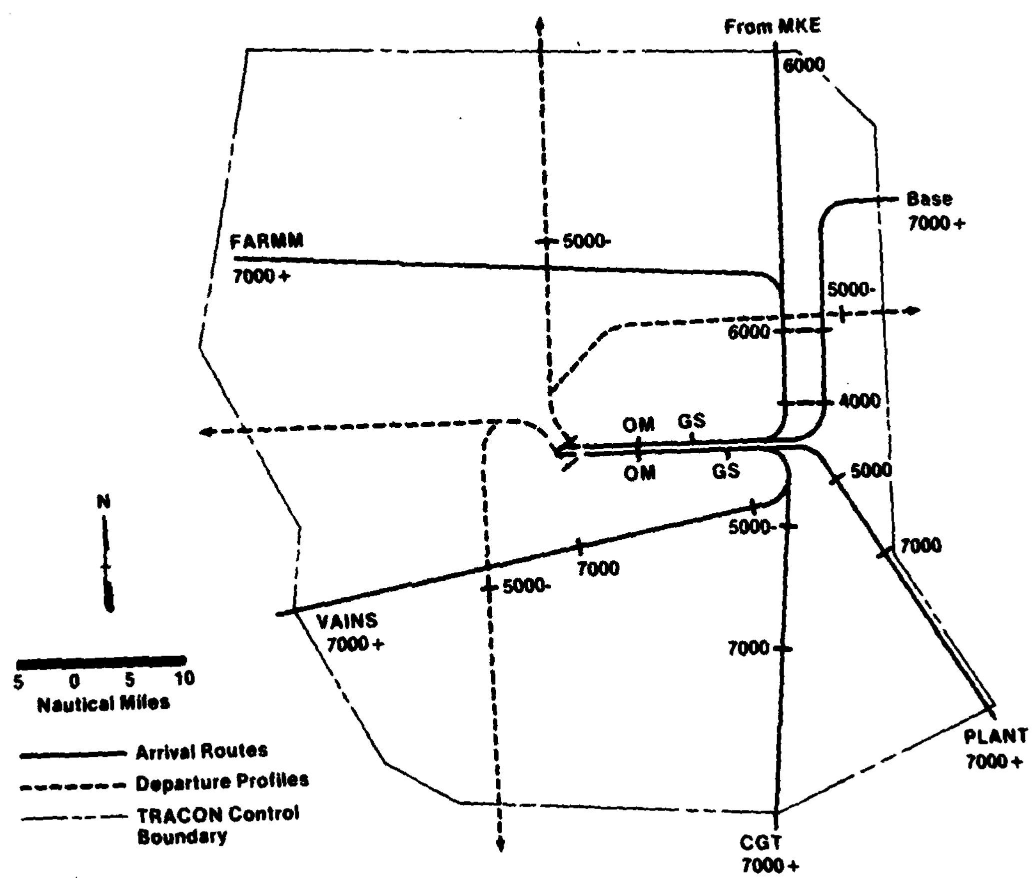

FIGURE 5-3
PROPOSED OPERATIONAL PROCEDURES FOR O'HARE USING HORIZONTAL MERGING

5.2.2 Vertical Merging

The vertical merging scheme described in Chapter 3 requires each runway to be fed by two traffic streams. In a manner similar to the horizontal merging scenario, traffic from the six fixes is merged to form four streams, two for each runway. As was the case for the horizontal merging scheme, for each runway both traffic streams can be loaded equally, independent of the instantaneous flow rates at each of the three fixes. Depending upon the particular design of the future WVAS system, it may be required, since vortices tend to drop, that all small aircraft be assigned to the high altitude stream and all heavy aircraft be assigned to the low altitude stream. Therefore, in Figure 5-4 each approach fix has been designed to provide a path to both the high and the low altitude streams.

Glide slope intercept altitudes of 4000 and 6000 feet MSL have been assigned, in this analysis, to the north side, and 5000 and 7000 feet MSL have been assigned to the south side. Reversal of altitudes has neither benefit nor penalty. However, if we assign 4000 and 5000 feet to one runway and 6000 and 7000 feet to the other, the region of required WVAS coverage increases from about 16.6 nmi to about 19.8 nmi (see Table 5-1). Also since the minimum localizer intercepts for the 6000 and 7000 foot streams are the same (see Table 5-1), an extension of one or the other may be required so that the two altitude streams are not collocated on a plan view display. This extension would bring the extended traffic stream right up to the TRACON boundary. One procedural advantage would be that the north side controllers could be assigned altitudes of 5000 feet and below and the south side controllers could be assigned 6000 feet and above. This may be easier to work with on an operational basis than the procedures required to implement the suggested vertical merging scheme.

Departure paths are very similar to those used in today's procedure. Like the horizontal merging case, the only change is that east-bound departures from runway 32R must maintain 5000 feet or below for about another three miles, compared to today's procedure.

5.2.3 Mixed Merging

An alternative to the use of either horizontal or vertical merging on both the north and south halves of the airport/airspace system is the use of a hybrid scheme. That is, horizontal merging could be used on one half and vertical merging used on the other. The advantage over vertical merging

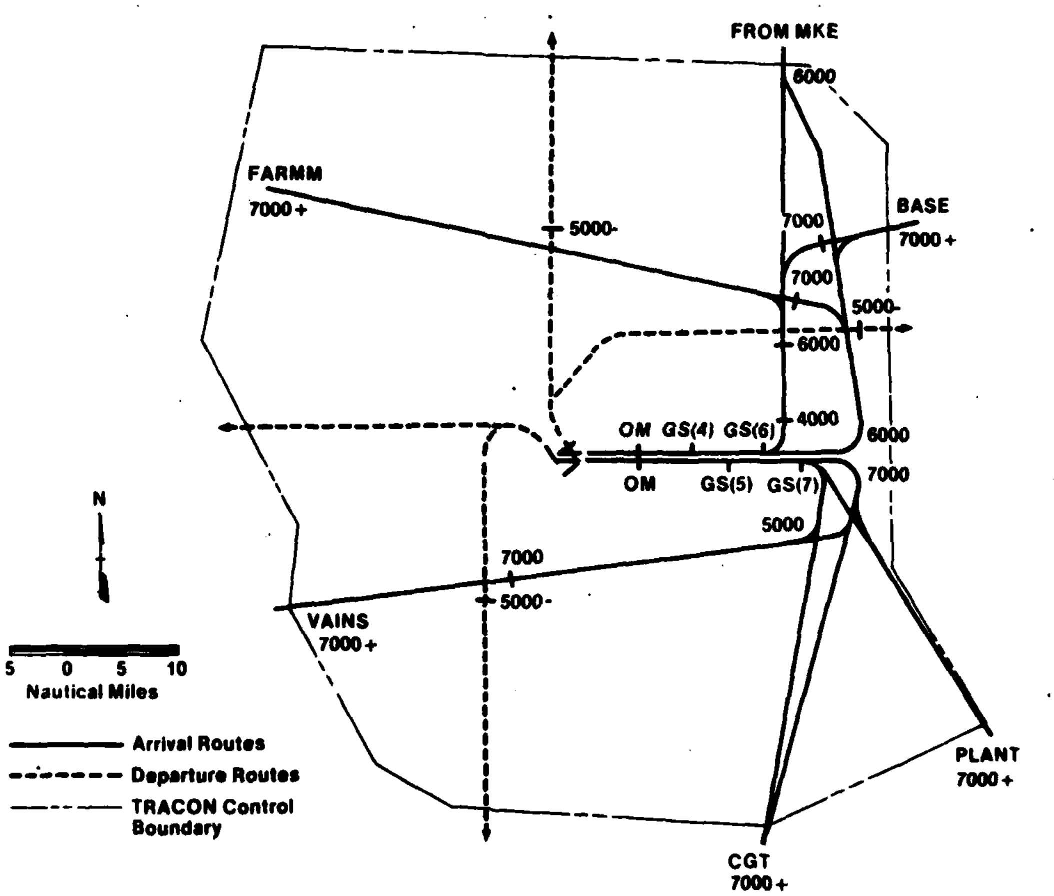

FIGURE 5-4
PROPOSED OPERATIONAL PROCEDURES FOR O'HARE USING VERTICAL MERGING

TABLE 5-1

INTERCEPTS AND REQUIRED COVERAGE

ALTITUDE (FEET)	GLIDE SLOPE INTERCEPT (NMI)	LOCALIZER INTERCEPT (NMI)		
		HORIZONTAL MERGING	VERTICAL MERGING	MIXED
4000	10.3	16.5	16.5	16.5
5000	13.5	16.5	19.6	19.6
6000	16.6	-	22.8	19.6
7000	19.8	-	22.8	-
		COVERAGE REQUIREMENT (NMI)		
		17.9	19.8 (4,5/6,7) 16.6 (4,6/5,7)	17.9 (H: 4; V:5,6) 21.0 (V:4,5; H:6)

is that only three altitude streams are required. However, with regard to the number of altitude streams, the mixed merging scheme is not as good as using horizontal merging on both halves, since this method employs only two altitude streams. It makes no difference which half of the airport uses each technique, but assigning 4000 feet to the horizontal merging scheme and 5000 and 6000 feet to the vertical merging scheme reduces the coverage requirement compared to other altitude assignments (see Table 5-1). This coverage requirement of 17.9 nmi. is the same as that required for horizontal merging but not quite as short as that required for vertical merging.

5.3 Transition To and From Reduced Spacings

The merging schemes described above are designed to enable aircraft to transition from one set of standards (outside of WVAS coverage) to another set of standards (in the region of WVAS coverage). This is a transition in space since the applicable set of standards is defined by the aircraft's position. Now a WVAS system that uses data pertaining to wind or the atmosphere as the criterion for the selection of separation standards is likely to change with time. The system may indicate that one set of standards is to be used on final approach and then, because of a change in the measured data, may indicate that a different set of standards should be used. Transition between these two sets of standards is a transition in time.

5.3.1 Missed Approach Analysis

A time transition from larger to smaller standards is no problem since if we maintain the larger standards there is no violation of standards. The only penalty is lost capacity, until arrival sequencing can be adjusted to the new set of standards. However, a transition from smaller to larger standards requires a procedure to avoid violating the larger standards. This procedure consists of selecting particular aircraft to execute go-arounds, while exercising speed control with the remaining aircraft to open or close particular interarrival gaps. An analysis to determine the number of go-arounds which would result from time transitions to larger standards was performed using the methodology described in Chapter 4 and Appendix A. This analysis was performed for all transitions from smaller to larger standards, and the results are presented in Table 5-2.

The analysis assumed that all aircraft that had not turned onto final approach, e.g., started the turn to intercept the localizer, could be rerouted by extending or "tromboning" the flight path. This extension of the flight path would probably

TABLE 5-2

PROBABILITY OF MISSED APPROACHES RESULTING FROM CHANGE IN SEPARATION STANDARDS AT O'HARE

ORIGINAL STANDARD	NEW STANDARD		
	TODAY'S	VAS	WVAS 2.5
WVAS 2.0 7AC*	(2)** 71% (3) 29%	(2) 98% (3) 2%	(2) 100%
WVAS 2.5 6AC*	(1) 36% (2) 64% (3) 0+%	(0) 2% (1) 98%	
VAS 5AC*	(1) 36% (2) 58% (3) 6%		

*NUMBER OF AIRCRAFT CONSIDERED FOR POSSIBLE MISSED APPROACH

**NUMBERS IN PARENTHESES INDICATE NUMBER OF MISSED APPROACHES

INTERPRETATION: WHEN THE SPACING STANDARD CHANGES FROM WVAS 2.0 TO TODAY'S, FOR THE 7 AIRCRAFT CONSIDERED, 71% OF THE TIME THERE WILL BE 2 MISSED APPROACHES AND 29% OF THE TIME THERE WILL BE 3 MISSED APPROACHES.

result in the TRACON boundary being violated. It is not known if this is a serious problem or how difficult it would be to have this boundary moved out, either temporarily or permanently. Coordination with the enroute center may be all that is required for a temporary violation of this boundary when required.

One difference between this analysis and the missed-approach analysis performed for Atlanta is the number of aircraft considered to be on the final approach. Compared to Atlanta, one additional aircraft was considered for each of the three sets of reduced separation standards (5 for VAS standards, 6 for 2.5 nmi WVAS standards, and 7 for 2.0 nmi WVAS, compared to 4, 5, and 6 aircraft for Atlanta). Since the mixes for the two airports are similar, it is felt that the differences in probabilities for missed approaches between the airports are probably due to the inclusion of the extra aircraft at O'Hare.

5.3.2. Warning Time Requirements

Because of the similarities between O'Hare and Atlanta, with regard to mix, localizer intercept distances, and distances from approach fixes, the time requirements are the same for both airports. These time requirements are given in Table 4-2 in the previous chapter.

5.4 Capacity Impacts

Previous sections have analyzed the feasibility of achieving reduced spacings on final approach. In this section the capacity benefits associated with the utilization of these reduced standards are estimated. Estimated capacities correspond to today's aircraft mix (17% small, 69% large, and 14% heavy).

Table 5-3 presents a summary of the percent increase in runway capacity, relative to today's standards. The capacity estimates were obtained by using the MITRE capacity model (Reference 10) with inputs developed and used by the Chicago O'Hare Delay Task Force. These inputs are given in Appendix B.

The percent increases given in Table 5-3 are valid for two scenarios: 100% arrivals, and 50% arrivals with a departure vortex system. This hypothetical departure vortex system assumes departure-departure spacings (in seconds) of 60/90/120 for VAS, 60/60/90 for 2.5 nmi WVAS, and 60/60/60 for 2.0 nmi WVAS. These large increases under mixed operations are possible because the independent departures-only runway provides excess

TABLE 5-3

CAPACTIY BENEFITS FOR O'HARE
USING VORTEX SYSTEM SEPARATIONS

SEPARATION STANDARD NAME	% INCREASE IN RUNWAY CAPACITY	
	ACCORDION EFFECT	VERTICAL OR HORIZONTAL MERGING
VAS	5.0	8.6
WVAS 2.5	14.8	19.8
WVAS 2.0	28.2	44.4

departure capacity, and it must be stressed that the increases for 50% arrivals are valid only for the selected configuration. Configurations without an independent departures-only runway would have a reduced benefit. If no departure-departure spacing reduction were available, i.e., 60/90/120 sec. separation was assumed for all cases, the only benefit to be reduced would be the 2.0 nmi WVAS with vertical or horizontal merging. The percent increase for this case would be 38.6%, rather than 44.4%. All other percent increases would be the same. As an example, consider the capacity benefits of the WVAS 2.0 set of separation standards, relative to today's standards. If the accordion effect is used to close up interaircraft spacings on final approach there will be a 28.2% increase in capacity. If one of the two merging techniques is used however, there will be a 38.6% increase with no departure vortex system. With the hypothesized departure vortex system there will be a 44.4% increase in capacity.

6. CONCLUSIONS AND RECOMMENDATIONS

Certain conclusions can be drawn from the analysis concerning the coverage requirements and relative capacity benefits of the three operational procedures investigated. The effects of different amounts of warning time before a required change in separation standards, with regard to probabilities of missed approaches and disruption of orderly traffic flow, have also been studied.

The use of the accordion effect to reduce spacings requires WVAS coverage up to the outer marker, about 5 miles from the runway threshold. This procedure achieves significant but partial potential capacity benefits. The vertical and horizontal merging schemes enable full capacity benefits to be attained from reduced separation standards where the minimum separation standard is as low as 2.0 nmi. These merging procedures require vortex system coverage of about 12 miles for a single runway, and approximately 17 to 20 miles of coverage for parallel runway configurations with independent arrivals on both runways.

A change in the required separation standards from smaller to larger standards requires a procedure which will avoid violation of the larger standards. This procedure consists of selecting particular aircraft to execute go-arounds, while using speed control to open or close the remaining gaps for aircraft on the localizer. The number of go-arounds and the required extension of the localizer intercept point (used to absorb traffic that have not yet intercepted the localizer) are dependent upon the amount of advance warning time given by the system before the new standards must be enforced. A warning time of 2.5 minutes results in a high probability of one or two missed approaches and a large extension of the downwind area. As the warning time is increased to about 8 minutes, the probability of missed approaches nears zero, but the large extension of the downwind area remains. A warning time of about 20 minutes allows stable transition between different standards, with no extension of the downwind area.

Comparing the hypothesized WVAS standards having 2.0 nmi minimum separation to today's IFR standards, the accordion effect can give approximately 28% increase in arrivals-only capacity (using the aircraft mixes observed today at Atlanta and Chicago). The use of either merging procedure yields an additional 16% increase in arrivals-only capacity.

The specific design of a future Wake Vortex Avoidance System should utilize the results of this study in incorporating the following parameters in its design tradeoff: (a) the type of standards involved, (b) the specific spacing reduction schemes, (c) vortex system coverage, (d) the availability of transition airspace, (e) the amount of warning time before a required change in standards, (f) the number of missed approaches considered acceptable, and (g) the associated capacity benefits.

APPENDIX A

DETERMINATION OF THE PROBABILITY OF MISSED APPROACH

The analysis described below gives a first order estimate of the probability that a given number of aircraft out of an arrival stream will execute a missed approach when the interarrival separations between aircraft are enlarged because of a change in vortex system requirements. This description outlines methods to find the average spacing between aircraft, the number of aircraft considered, the amount of change in spacing between aircraft that can be made, and the probability of missed approach.

The percent mix of aircraft for the three types of aircraft is given by α_i, i= 1,2,3, where $\sum_i \alpha_i = 1$, and the subscripts designate (1) small, (2) large and (3) heavy aircraft respectively.

The percent mix for a particular aircraft pair is $\alpha_i \alpha_j$ where $\sum_i \sum_j \alpha_i \alpha_j = 1$. The interarrival separations required between aircraft outside the outer marker so that they will be at the minimum IFR standards at closest point of approach is $S_{ij}^{(k)}$, where i and j designate the aircraft pair, and k designates the vortex system requirement, i.e., (1) today's, (2) VAS, (3) WVAS 2.5, and (4) WVAS 2.0 The transition between standards with separations $S_{ij}^{(k)}$ and $S_{ij}^{(n)}$ is considered for those in which the interarrival spacings become larger, i.e., $k-n > 0$. These transition matrices are shown in Figure A-1. The average separation between aircraft is determined by $S_{ave}^{(k)} = \sum_i \sum_j \alpha_i \alpha_j S_{ij}^{(k)}$. The number of aircraft within 15 nmi. of the outer marker is obtained by $N^{(k)} = 15/S_{ave}^{(k)}$ rounded to the nearest integer.

ORIGINAL STANDARD	NEW STANDARD	LEAD	TRAIL S	TRAIL L	TRAIL H
WVAS 2.0	TODAY'S	S	1.3	1.2	1.2
		L	1.8	1.2	1.2
		H	3.3	2.8	2.3
WVAS 2.0	VAS	S	1.3	1.2	1.2
		L	.6	1.2	1.2
		H	1.2	.5	1.1
WVAS 2.0	WVAS 2.5	S	.6	.6	.5
		L	.6	.6	.5
		H	.6	.5	.6
WVAS 2.5	TODAY'S	S	.7	.6	.6
		L	1.2	.6	.6
		H	2.7	2.3	1.7
WVAS 2.5	VAS	S	.7	.6	.6
		L	0	.6	.6
		H	.6	0	.5
VAS	TODAY'S	S	0	0	0
		L	1.2	0	0
		H	2.1	2.3	1.2

NOTE: THESE MATRICES REPRESENT THE ADDITIONAL IN-TRIAL SEPARATION REQUIRED BETWEEN AIRCRAFT ON THE LOCALIZER OUTSIDE THE OUTER MARKER

FIGURE A-1
TRANSITION MATRICES RESULTING FROM CHANGE IN SEPARATION STANDARD

The effect of speed control on the separation between aircraft is shown in Figure A-2. The assumptions are that the initial speed of the aircraft is 180 knots, and it has an acceleration of one knot per second. The graph shows the amount of change in separation between aircraft as a function of the distance flown by the two aircraft after the speed command is given.

The objective is to increase separation between aircraft. The availability of the speed control is determined by the strategy used to change the interarrival spacing (as previously described in Figure 4-5). The distances at which the speed control is determined is given by $d_m^{(k)} = (m-1)\, S_{ave}^{(k)}$, which are multiples of the average separation between aircraft. Here the index m refers to the m^{th} aircraft, where the first aircraft is assumed to be just outside the outer marker. The increase in separation for the distance $d_m^{(k)}$ is obtained from Figure A-1, and are designated C_m^{inc} if the speed is increased, and C_m^{dec} if the speed is decreased. The total amount of control available between aircraft m-1 and aircraft m is $C_{m-1}^{inc} + C_m^{dec}$. The strategy for increasing speed is only available if the prior aircraft is to execute a missed approach (thus creating a gap in the arrival stream).

The first aircraft in the arrival stream (located just outside the outer marker) is allowed to land. The probability that it will execute a missed approach is zero.

$$P\,(M_1) = 0$$

$$d_1^{(k)} = 0$$

$$c_1^{inc} = c_1^{dec} = 0$$

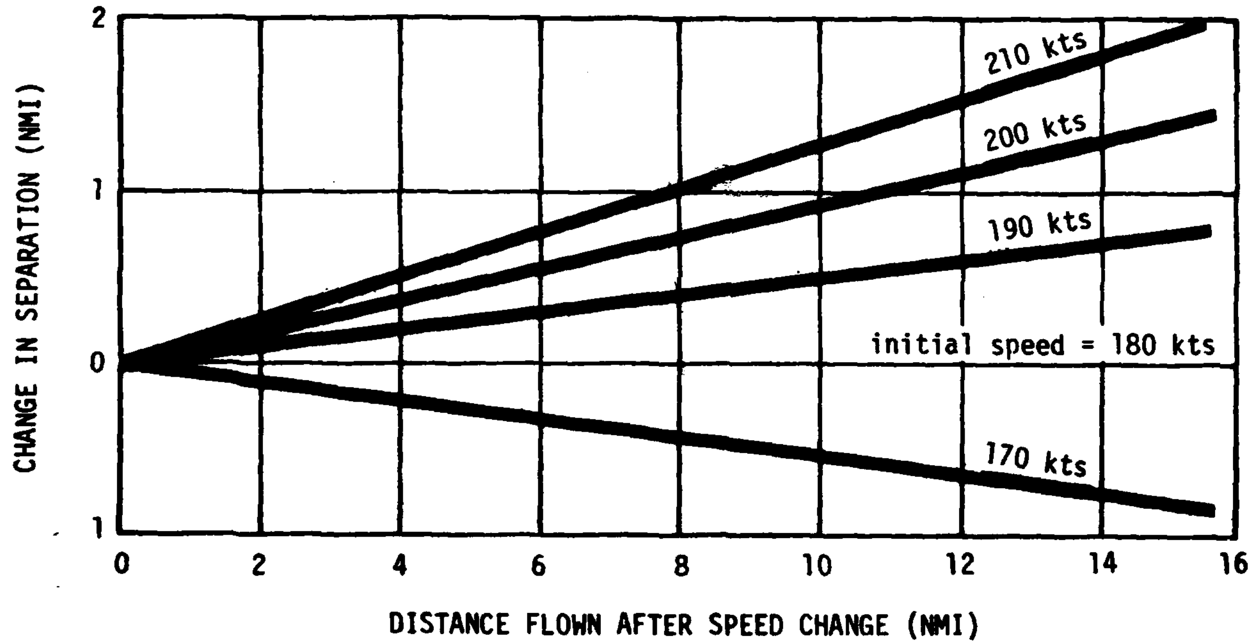

FIGURE A-2
EFFECT ON SPEED CHANGES ON SEPARATION BETWEEN AIRCRAFT

An aircraft will execute a missed approach if the change in separation standard is greater than the amount of control from speed changes. This condition is designated

$$P(M_m) = 1 \text{ if } (S_{ij}^{(n)} - S_{ij}^{(k)}) > (C_{m-1}^{inc} + C_m^{dec})$$

If an aircraft does execute a missed approach, the next aircraft in the arrival stream is allowed to land, i.e.

$$P(M_m) = 0 \text{ if } P(M_{m-1}) = 1.$$

The following outlines the computation of probability of missed approach for changing the separation standard from VAS to 3/4/5/4/6 at Atlanta Airport.

The mix at Atlanta is $= [.14 \quad .73 \quad .13]$

The average separation using VAS standard from Figure 3-4 is

$$S_{ave}^{(2)} = \alpha[S^{(2)}]\alpha^T$$

$$S_{ave}^{(2)} = [.14 \quad .73 \quad .13] \begin{bmatrix} 4 & 4.2 & 4.4 \\ 3.7 & 3.7 & 3.9 \\ 4.6 & 3.4 & 3.4 \end{bmatrix} \begin{bmatrix} .14 \\ .73 \\ .13 \end{bmatrix} = 3.8$$

The number of aircraft considered is

$$N^{(2)} = 15/3.8 = 3.9$$

Rounding yields

$$N^{(2)} = 4 \text{ aircraft}$$

The controllability from change in speed is

Aircraft (m)	Distance (d_m^2)	Increase in Separation C_m^{inc}(+20kts)	C_m^{dec} (- 10kts)
1	0.	0	0
2	3.9	.4	.2
3	7.8	.7	.4
4	11.7	1.2	.6

The change in standard from VAS to 3/4/5/4/6 from Figure 3-4 is

$$S^{(2)} - S^{(1)} = \begin{bmatrix} 0 & 0 & 0 \\ 1.2 & 0 & 0 \\ 2.1 & 1.2 & 1.2 \end{bmatrix}$$

The probability of one missed approach is

$$P1 = P(M_2)\ P(\bar{M}_3, \bar{M}_4 \mid M_2) + P(\bar{M}_2, M_3)\ P(\bar{M}_4 \mid M_3) + P(\bar{M}_2, \bar{M}_3, M_4)$$

$$P1 = (.24)\ (.88) + (.21)\ (1) + .15$$

$$P1 = .57$$

$P(M_2)$ = probability that the 2nd aircraft will execute a missed approach which happens when the change in separation is greater than C^{dec} or .2 nmi. This happens for the matrix elements from $[S^{(2)} - S^{(1)}]$ for (2,1), (3,1), (3,2) and (3,3). From the $[\alpha^T\alpha]$ matrix, these elements have a probability of .24.

$P(\bar{M}_3 \mid M_2)$ = probability that the 3rd aircraft will not execute a missed approach, since the 2nd aircraft exits from the arrival stream creating a gap. (= 1, by assumption)

$P(\bar{M}_4 | \bar{M}_3)$ = probability that the 4th aircraft will not execute a missed approach. The 3rd aircraft can speed up 20 knots and the 4th aircraft slow down 10 knots producing a total controllability of $C^{inc} + C^{dec} = 1.3$ nmi. The matrix elements (3,1) and (3,2) of $\left[S^{(2)} - S^{(1)}\right]$ are greater than this amount. From the $\left[\alpha^T\alpha\right]$ matrix, the elements which are smaller have a probability of .88.

$P(\bar{M}_2, M_3)$ = probability that the 2nd aircraft will not have a missed approch and the 3rd aircraft will have one. The controllability for the 3rd aircraft from slowing down is .4 nmi. The sequences which satisfy this condition are SLS, SHS, SHL, SHH, LLS, LHS, LHL, LHH which have a probability of .21.

$P(\bar{M}_4 | M_3)$ = probability that the 4^{th} aircraft will not execute a missed approach, since the 3^{rd} aircraft exits from the arrival stream creating a gap. (= 1, by assumption)

$P(\bar{M}_2, \bar{M}_3, M_4)$ = probability that the 2nd and 3rd aircraft will not have a missed approach, and the 4th aircraft will. The controllability for the 4th aircraft from slowing down is .6 nmi. The sequences which satisfy this condition are [SSLS, SSHS, SSHL, SSHH, SLLS, SLHS, SLHL, SLHH, LLLS, LLHS, LLHL, LLHH] which have a probability of .15.

APPENDIX B

INPUT DATA USED IN THE CAPACITY ANALYSES

The estimates of capacity were obtained using the MITRE capacity model (Reference 10). The model uses four aircraft classes, denoted as S, L_1, L_2, and H, and defined as follows:

Class S - small - aircraft with maximum gross takeoff weight (GTOW) of 12,500 pounds, or less

Class L_1 - large - aircraft with maximum GTOW between 12,500 pounds and 90,000 pounds

Class L_2 - large - aircraft with maximum GTOW between 90,000 pounds and 300,000 pounds.

Class H - heavy - aircraft with maximum GTOW of 300,000 pounds or more.

The following input data was used in estimating capacity at Atlanta and O'Hare.

	S	L_1	L_2	H
Aircraft Mix - Atlanta (%)	14	20	53	13
- Chicago (%)	17	4	65	14
Approach Velocities (outside O.M.) (Kts.)	160	160	160	160
Final Velocities (Inside O.M.) (Kts.)	120	130	130	140
Arrival Runway Occupancy Protection Time (includes buffer) (sec.)	34	41	49	52
Departure Runway Occupancy Protection Time (includes buffer) (sec.)	20	34	39	39
Time for Arrival to Clear Intersection -ORD-27R/32R (sec.)	8	8	5	5
Time for Departure to Clear Intersection -ORD-27R/32R (sec.)	10	10	8	10

Distance to outer marker	5 nmi
Interarrival Delivery Error (Standard Deviation)/number of Standard Deviations Protected	18 sec./1.65 - Today, VAS, WVAS 2.5 11 sec./2.33 - WVAS 2.0

APPENDIX C

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